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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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ENTRAPMENT OF AIR IN BEACH SAND

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Contributions from the Scripps Institution of Oceanography
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ABSTRACT

Sand holes, sand domes, and cavernous sand are common minor beach features. All appear to be formed by air being forced out of pore spaces in the sand because of the entrance of water. The features may be of some geological significance in determining the order of deposition of steeply dipping sandstones and, if present in great abundance, may be indicative of a marine depositional environment.

INTRODUCTION

It is a common observation that on the upper part of most sand beaches a large amount of air is expelled from the sand when a wave washes up the beach slope. Most of this escaping air forms bubbles which rise through the water as it runs back down the beach slope. Even after the sand surface is re-exposed, air continues to escape for a short time as shown by the continued formation of numerous small holes in the surface, and sometimes by a local doming of the sand surface. In escaping or attempting to escape from the sand, the air may produce sand holes, sand domes, or cavernous sand. Where recognized in ancient consolidated sediments, these features may be indicative of a special environment and have other geological significance.

Sand holes, sand domes, and cavernous sand were studied intermittently over a period of about two years at many beaches near San Diego, Mission Bay, and La Jolla, California. All three features were also found during short visits to be present on favorable parts of other Pacific Ocean beaches at San Francisco, Santa Monica, Long Beach, Huntington Beach, Newport Bay, and Cardiff, California, and at Atlantic Ocean beaches at Martha's Vineyard, Mass.; New London, Conn.; Cape May, N. J.; Norfolk, Va.; San Augustine, Fla.; Miami, Fla.; Bermuda; and Recife, Brazil. Sand holes and either sand domes or cavernous sand were seen on beaches at Woods Hole, Mass.; Manhattan Beach, N. Y.; San Juan, Puerto Rico, Panama, C.Z., and the Salton Sea. On beaches at Key West, Fla., and Galveston, Texas, the features could not be found. Neither were they found on brief examination of beaches of Lake Michigan, Lake Worth in Texas, and small reservoirs in California. It is apparent, however, that the features have very widespread distribution.

The writer is especially indebted to Dr. Martin Johnson and Mr. E. C. LaFond for suggestions regarding origin of the features. Ideas were also contributed by many others during informal discussions.

SAND HOLES

In escaping from beach sand, air usually is concentrated in several steady streams, each emerging from a hole between 1 and 10 millimeters in diameter. On flat parts of a beach where the water runs back downslope slowly, or on the backslope where water may collect in shallow ponds at high tide, most of the air escapes into the water as bubbles. Agitation of the water by the bubbles results in the formation of a crater, commonly about 2 centimeters deep and 5 centimeters wide, at the mouth of the hole. These craters appear to be small-scale relatives of craters formed in mud through the action of escaping gas bubbles as described by Maxon (1940). Another type of mouth consists of a raised rim about 1 millimeter high and 5 millimeters wide closely surrounding the hole. These rimmed openings are some-

times formed when the sand is covered by only a thin film of water. A third type of hole is common on steep parts of a beach where the water runs downslope so quickly that most of the air escapes from the holes directly into air. The mouth of each of these holes is sharp-edged, with no suggestion of a crater or a raised rim (pl. 1, fig. 1). The sharp-edged holes are sometimes formed on gentle slopes also, after the water has run back downslope and bared the sand. Both the cratered and the sharp-edged holes are very common, but the type having a raised rim is rare. All three types are shown in plate 1, figure 2.

On excavating the sand around a hole, one finds that most of the holes are between 1 and 4 centimeters deep. Many have ramifying feeder channels at the bottom, much as described by Palmer (1928).

Somewhat similar holes are formed at the very highest part of beaches by burrowing crustaceans (Emery, 1944). The broad shallow holes formed by drips from ledges, and by raindrops have entirely different characteristics and are not apt to be confused with those caused by the escape of air (Twenhofel, 1932, p. 678).

SAND DOMES

Frequently associated with sand holes are domes or areas where layers of sand are uplifted above an air pocket which has the shape of a laccolith (pl. 2, fig. 1). The sides of the sand dome usually constitute a smooth gentle slope to the highest point at the center of the dome. Occasional small domes, however, have steep abrupt side slopes rising to a flat mesa-like area. The sand domes range from about 2 to more than 15 centimeters in diameter and from a few millimeters to about 3 centimeters in height. The "air laccolith" has approximately the same height, but a somewhat smaller diameter than the domed sand surface. It sometimes caps a feeder hole similar to other sand holes that extend to the surface, but usually there is no trace of a feeder hole. Similar domes have been briefly described by Reade (1884), Palmer (1928), Twenhofel (1932, p. 685), and Johnson (1938).

Sand domes occur chiefly on the upper part of a beach and usually form near the uppermost reach of a wave when the water begins running back downslope. Sometimes successive waves form domes along roughly parallel lines, each line marking the position of farthest advance of a wave. One beach was observed to have seven separate such areas of sand domes.

Almost invariably the sand domes are restricted to beaches having thin layers of coarser sand alternating with layers of finer sand. The "air laccoliths" are formed in the coarser layers (pl. 2, fig. 1). On many beaches the coarser grained layers consist of shell fragments and the finer grained layers of detrital sand of almost the same color. However, some of the California beaches consist of alternating dark and light colored laminae of detrital sand, as described by Thompson (1937). An attempt was made to find the grain size in each type of lamina of the beach near Scripps Institution of Oceanography. Median diameters of 0.190 millimeters for the light colored sand and of 0.165 millimeters for the dark heavy mineral sand were obtained, but because of the impossibility of sampling either lamina without including some sand from the other lamina, the actual size difference of laminae on this beach is greater than these figures indicate. A dye injected into this laminated sand just before it was covered by a wave was later found to have drained downdip 15 centimeters in the coarser laminae in contrast to only 3 centimeters in the finer laminae, thus indicating a differential horizontal permeability. A similar relationship for laminae of dune sand was described by Bagnold (1942, pp. 237, 238).

Where sand domes are formed in beaches composed of alternating dark and light colored laminae, striking patterns are formed after partial erosion of the sand domes, as shown in plate 2, figure 2. Usually the first wave which washes over a newly formed sand dome truncates it at a level even with the gen-

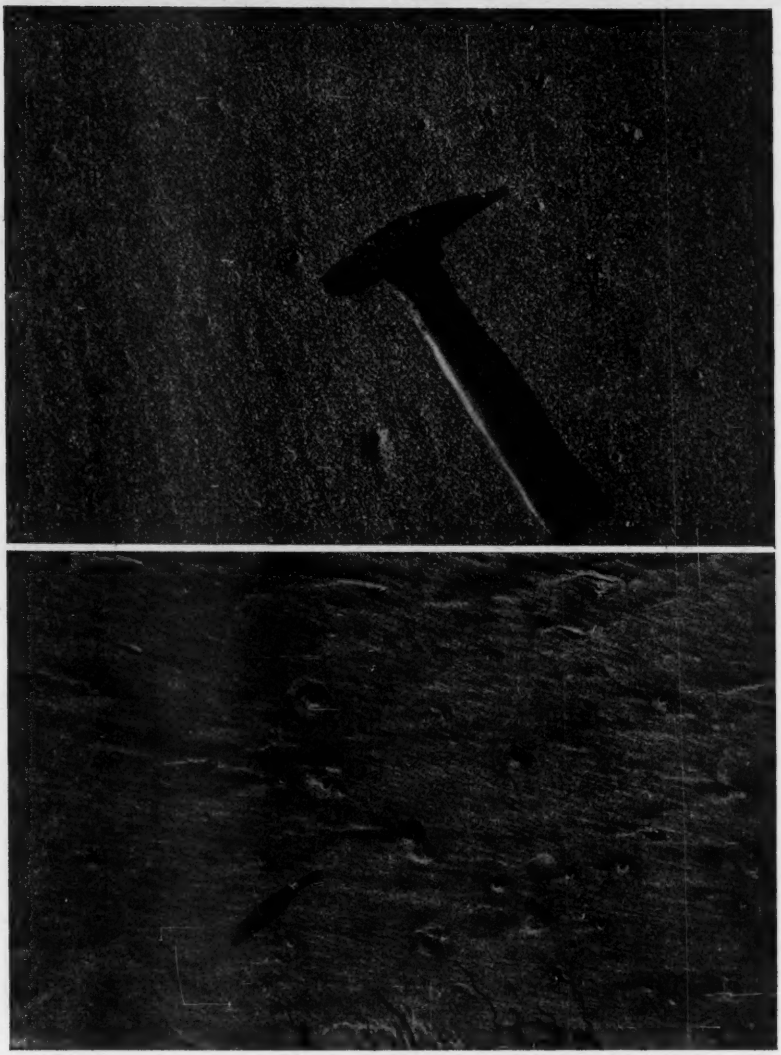

PLATE 1

FIG. 1.—Sand holes in coarse sand beach at south La Jolla, California. Beach slope is about 5 degrees.

FIG. 2.—Sand holes in fine sand beach at entrance to Mission Bay, California. Many of the holes have crater-like mouths. A few other holes are surrounded by small raised rims, and some of the smaller holes have sharp-edged mouths like those of figure 1. Note the sand dome about 20 centimeters right of the knife. Beach slope is 1 degree.

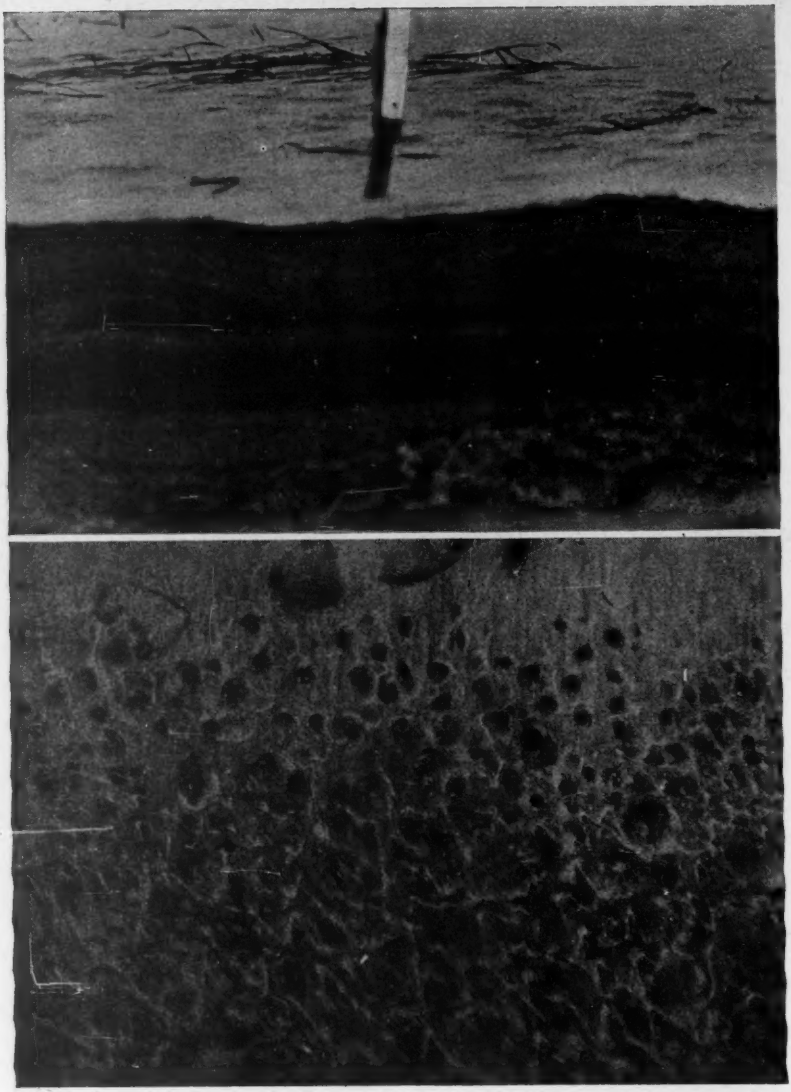

PLATE 2

FIG. 1.—Sand domes exposed in cross-section of well laminated fine sand beach near Scripps Institution of Oceanography, La Jolla, California. Dome at left was formed and the upturned laminae were bevelled. A layer of nearly horizontal laminated sand was deposited, after which the dome at right was formed but not yet truncated. Note the numerous sand domes in the background. Beach slope is about 3 degrees.

FIG. 2.—Surface of the same beach showing appearance of smaller domes which were truncated so that successively deeper laminae are exposed. Domes near bottom have been partly destroyed or buried by later waves. Note the presence of sand holes near the center of some of the truncated domes.

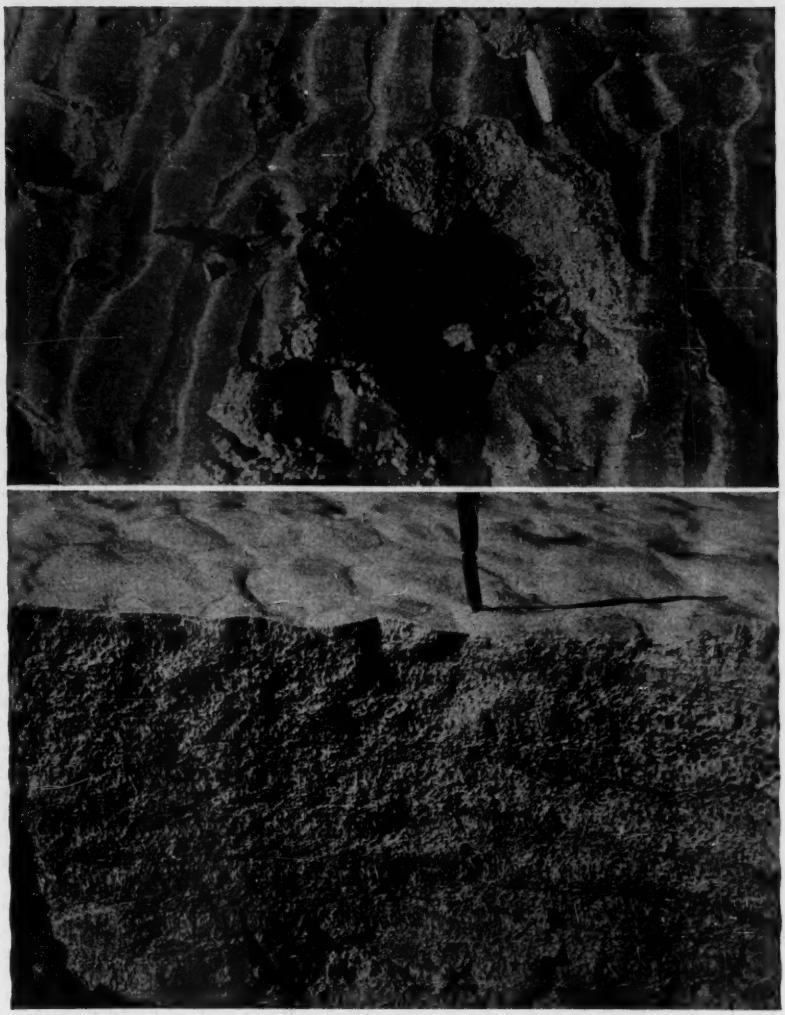

PLATE 3

FIG. 1.—Cavernous sand on ripple-marked fine sand beach near entrance to Mission Bay, California. Cavernous layer is about 5 centimeters thick. Beach slope is 2 degrees.

FIG. 2.—Cavernous sand at same beach in layer 25 centimeters thick. Beach slope is 5 degrees.

eral beach surface. If the height of the sand dome is such that the truncation includes part of a dark lamina, the position of the sand dome is marked by a black spot. If another sand dome is higher, the second lamina of light sand may be exposed, leaving the position of that sand dome marked by a dark ring. Both types of markings are present in the area of plate 2, figure 2. After truncation, the sand domes may be buried by a later fill of sand having horizontal laminae ex-

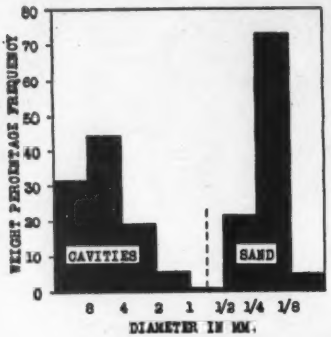

FIG. 1.—Histograms showing size variation of sand grains and of ellipsoidal cavities in sand illustrated in plate 3, figure 2. Note that both histograms show size distribution by weight (or volume) percentage frequency and not by numerical percentage frequency.

tending across the bevelled edges of the lower tilted laminae (pl. 2, fig. 1). Some of the larger domes collapse after truncation and their position is marked by a slight depression instead of a domed area.

CAVERNOUS SAND

In addition to laccolith-shaped air pockets, numerous small ellipsoidal cavities are present in a layer several centimeters thick in many beaches. On some beaches these layers were found to be 20 to 30 centimeters deep (pl. 3, fig. 2). The texture is similar to that of coarse bread. The diameter of these cavities is many times that of the sand grains which form the smooth cavity walls. Careful breaking of lumps of this sand shows that few of the cavities are connected either with each other or with the sand surface. In shape, the cavities vary from spheres to rough ellipsoids elongate in the bedding plane. Where only a few cavities are present, they usually occur in rough alignment along a coarse lamina. Where more abundant, they occur in a layer several centimeters thick and may be independent of laminae.

Mechanical analysis of a typical cavernous sand layer from Mission Bay showed the sand to have a median diameter of 0.190 millimeters. For comparison, the maximum diameter of all cavities exposed by breaking a lump of cavernous sand was measured with a transparent ruler having a millimeter scale. The median diameter based on the diameter frequency distribution of 603 cavities counted is 1.8 millimeters. Since this median diameter is based on the numerical frequency of cavity diameter it is not directly comparable with the 0.190 millimeter median diameter of the sand grains because the latter is based on weight frequency distribution (Krumbein and Pettijohn, 1938, pp. 225–227). Converted to volume (or weight) frequency distribution, the ellipsoidal cavities are revealed to have a median diameter of 5.8 millimeters, or about 30 times the median diameter of the sand grains which form the cavity walls (fig. 1).

The total porosity of the cavernous sand was assumed to consist of the volume of the ellipsoidal cavities plus the normal porosity between tightly packed grains of sand. The aggregate volume of the cavities was measured by compacting underwater a core of the sand 8.2 centimeters in diameter and 10.6 centimeters in length until all settling ceased and no bubbles of air were given off when the sand was stirred by a thin rod. Compaction of the most porous sand found at Mission Bay to a length of 6.8 centimeters showed that the cavities constituted 36 per cent of the volume of the original sand mass. By weighing the wet sand, drying it, and reweighing, the weight of the interstitial water and thus the intergranular pore space was found to be 37 per cent of the compacted sam-

ple, or 24 per cent of the original sample. This method introduces an error of probably not more than 1 per cent because the pore space adjoining one side of each sand grain facing a cavity is included in both measurements. The total original pore space then is 36 plus 24 minus 1 equal 59 per cent by volume.

Cavernous sand, like the sand holes and sand domes, is most common near the upper part of the beach reached by the tide, and the three features are usually closely associated. When covered by high tide, the layers of cavernous sand give out great clouds of bubbles after being walked on or otherwise disturbed. These bubbles obviously are from the cavities as examination of numerous lumps of the sand has revealed only air, never water, within the cavities.

The sand is softest immediately after being exposed by a retreating tide. Apparently the surface tension of the interstitial water is sufficient to hold the sand grains in place around the cavities but is not able to give the mass of sand much strength against local outside forces, so that footprints penetrate almost the entire thickness of the cavernous sand layer. After drying to the stage where little or no interstitial moisture is present, the sand is firmer, supposedly because of deposition of a sea-salt cement between the sand grains. In several instances, the cavernous sand was found immediately underlying a ripple-marked surface (pl. 3, fig. 1). However, it usually underlies a smooth surface and may be buried under several centimeters of firmly packed sand which is separated by a sharp contact and is known to be a more recent deposit. When one walks over a beach having compact sand overlying cavernous sand, the beach may appear quite firm so that light steps leave only shallow footprints. However, if by heavier steps the surface layer is broken, footprints may become very deep.

RELATION TO BEACH CHARACTERISTICS

There is a rough relationship of the sand holes, sand domes and cavernous sand to the size of sand grains. In general, they are present or abundant in coarse, medium, and fine-grained sand, and rare or absent in very coarse and very fine sand. All the features are abundant only at the upper part of the beach reached by high tide. Cratered sand holes are common only on the backslope, while the simple sharp-edged holes are found on all parts of the upper beach, on both flat and steep beaches, and even on vertical erosional slopes. Sand domes and cavernous sand are rare on slopes of more than about 8 degrees. Sand domes are best developed in laminated sand, while both sand holes and cavernous sand are less closely related to laminae.

Although cavernous sand is present on most beaches of intermediate grain size, it usually is far less well developed on beaches exposed to large waves than on the more protected beaches of bays. Typically, the thickness of the cavernous sand layer on beaches facing the open ocean is not more than 4 centimeters, in contrast to layers of 30 centimeters thickness which have been observed in bays.

SAND DUNES

After a heavy (2.5 centimeter, according to U. S. Weather Bureau records) overnight rainfall, the sand of dunes near San Augustine, Fla., was found to be wet to a depth of about 4 centimeters. A number of sand domes were found in the wet layer of sand, and cavernous sand occurred in the flat basins between dunes. When the sand dried during the following day, the domes were destroyed through erosion by wind-blown sand.

LAKE BEACHES

Sand holes, sand domes, and cavernous sand have not been reported for lake beaches so far as the writer is aware. Observations on beaches of Lake Michigan and small reservoir lakes in Texas and California failed to reveal the features. However, sand holes and sand dunes were found on a beach of the Salton Sea after a period of high waves but neither were as abundant as on most marine beaches. It is possible, therefore, that they may form on beaches of large lakes during times of occasional very high waves or seiches.

AIR PRESSURE IN THE SAND

The escape of air from dry beaches just as they are first covered by water at high tide was described by Cornish (1912) and by Kindle (1926). However, even after the upper part of a beach has been wet by previous waves, more air may escape when another wave washes up the beach slope, provided several minutes elapse between waves. The escape of air is shown by the presence of streams of bubbles rising through the water, and by the continued formation of small sand holes shortly after the water has run back downslope. On the seaward sloping portion of a beach the escape of air caused by a single wave lasts only a minute or two. However, on the backslope, where water may collect in shallow pools at high tide, air has been observed to escape for about two hours. The pressure of the escaping air is sometimes sufficient to form a fountain reaching about five centimeters above the surface of these pools.

A simple means of measuring the air pressure was made by attaching an inverted glass funnel to an open U-tube manometer half filled with distilled water colored by potassium permanganate. The large end of the funnel was pushed about 5 millimeters into the sand over a hole through which air was escaping and the pressure of the air determined by measuring the difference in height of the colored water in each side of the U-tube.

About a hundred measurements were made during successive waves at high tide on a fine sand beach sloping 7 degrees at a spot a few meters from the cavernous sand illustrated in plate 3, figure 2. The waves were 1 to 10 centimeters deep at the site of the measurements. A composite curve showing the pressure variation with time is illustrated in figure 2. Some of the individual measurements showed higher pressures, and others lower pressures but the composite curve is probably typical. It will be noted that immediately after the sand was covered by a wave the pressure of air escaping from a sand hole rose abruptly and reached a

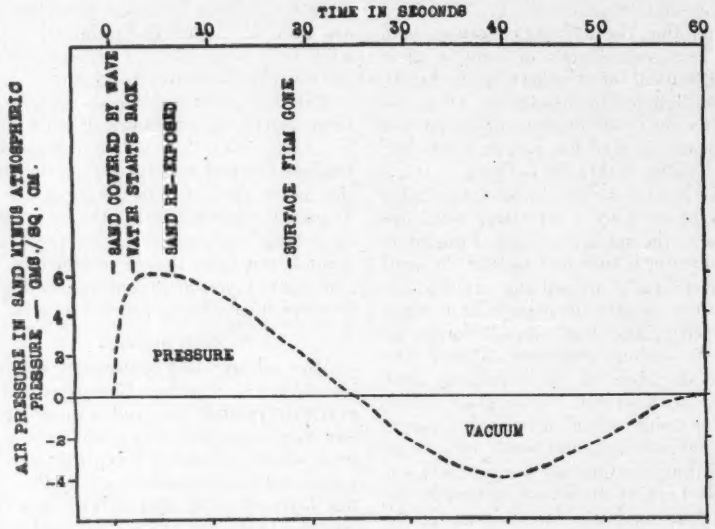

FIG. 2.—Variation of air pressure in fine sand following the wash of a wave up the beach slope.

maximum about 4 seconds after the wave covered the sand. These maximum pressures depended more on the time interval between waves than on the wave height. A typical maximum pressure was 6 grams per square centimeter, or about 1.4 ounces per square inch. At about 6 seconds the water had re-exposed the sand except for the presence of a thin surface film which disappeared at about 18 seconds. The pressure dropped roughly linearly during the period between 6 and 25 seconds after the wave covered the beach, following which it was again zero (equal to atmospheric pressure). However, after reaching zero, the pressure in the funnel continued to drop, forming a slight vacuum until about 40 seconds when the pressure was about 4 grams per square centimeter below atmospheric pressure. The pressure difference then gradually decreased so that at about 60 seconds the pressure within the funnel equalled atmospheric pressure. In the area within a few centimeters of the site of the measurements, bubbles rose through the sand between 2 and 6 seconds, forming a few very small cratered holes. From 6 to 25 seconds numerous sharp-edged holes and a few small sand domes formed.

On the nearby backslope of the beach a pool of water collected as the waves washed over the highest part of the beach at high tide. Air escaped from cratered holes within the pool for about 20 minutes. The maximum pressure measured was 23 grams per square centimeter, or 5.2 ounces per square inch.

Similar measurements were made during successive waves on a very coarse sand beach sloping 12 degrees and in which only a few sand holes were present. A typical maximum pressure was 10 grams per square centimeter, and a typical vacuum only 2 grams per square centimeter. The entire period of pressure variation was about 10 seconds.

ORIGIN

Sand holes, sand domes, and cavernous sand are usually found in the same general environment, on the highest part of a beach reached by high tide. On most beaches all three features are closely associated. None are common in very fine or very coarse sand, but all occur in sand of intermediate grain size. Only air is found in the sand holes and their feeder channels, in sand domes, and in the cavities of cavernous sand.

It is suggested that as a wave recedes, the sand becomes partly drained and the spaces between sand grains partly filled with air. As the next wave rapidly advances over the beach slope, the interstitial water also works up-dip, but more slowly. As a result, when the wave reaches its maximum height on the beach, the front of the slowly moving mass of interstitial water may be left several feet behind. Part of the water of the wave begins soaking into the beach sand. Air already in the sand pore spaces may then be trapped between the water soaking downward near the point of farthest advance of the wave and the interstitial water working back up-dip. This air may be forced out of the sand, developing sand holes en route. Palmer (1928) proposed a somewhat similar origin but only for beach sands consisting of alternating coarse and fine grained laminae. Actually, sand holes may form in unlaminated sand.

Where the beach is well laminated, as described by Thompson (1937), the water drains down-dip more rapidly in the coarser than in the finer laminae and is replaced by air as the wave retreats. When the next wave advances, the air is driven along the coarser layers and collects in pockets. If the overlying layer of wet fine sand is air tight, it may be arched upward and a sand dome is formed as described also by Palmer (1928) and by Johnson (1938). Domes may also be formed by the washing of a plug of sand into a sand hole through which air is escaping (Emery, 1944).

The presence of air in cavernous sand and the general similarity of environment and association of cavernous sand and the sand domes and sand holes suggests a

similar origin. The origin of cavernous sand by trapping of air between interstitial water advancing up-dip and water soaking downward through the sand was in fact, suggested by Kindle (1936). Trefethen (1941) objected to this origin but offered only the suggestions that soft or cavernous sand is the result of open packing developed by the lifting effect of escaping air, or by reworking by wind and organisms. A careful search for organisms, such as sand hoppers, which might be capable of forming the cavities at Mission Bay failed to reveal their presence. Also, cavernous sand was found at several places which were well protected from the wind. The entrapment of air in the sand, moreover, seems to be the only process capable of forming cavities having a diameter more than 30 times that of the sand grains forming the cavity walls.

A further indication of the relationship between the features and the entrapment of air is shown by the fact that the features are rare or absent in very coarse or very fine-grained sand. Very coarse sand has such large intergranular spaces, and consequent high permeability, that the air can escape so easily that sand domes and cavities cannot be formed. The very fine-grained sand beaches such as those near Galveston, Texas, do not permit rapid drainage of interstitial water and, as a result, air is not admitted and thus cannot be trapped.

Drainage of the upper part of the beach can take place only when the water table is low, or during low tide. The most complete drainage and, therefore, the most favorable conditions for formation of cavernous sand should exist at the bi-weekly periods of spring tides when the lowest tides and the largest tide ranges occur. The neap tides, correspondingly, should offer the least favorable conditions. Ranges between low tides and high tides of 2.6 meters at the time of spring tides and 1.3 meters at neap tides are typical. Measurements of the thickness of cavernous sand at the site of plate 3, figure 2 were made daily throughout one bi-weekly tidal cycle and at irregular intervals during 4 other bi-weekly cycles. Thickness of the layer was taken as the maximum depth of footprints. It was found that the thickness averaged about 15 centimeters for about 5 days beginning with the day of spring tide. Afterward, it gradually decreased to about 5 centimeters until the next spring tide, when it increased rather suddenly to about 15 centimeters. The sequence was repeated during the next bi-weekly tidal cycle. Similarly, a few measurements near the site of plate 2 showed a range of 5 centimeters during one or two days after spring tide to less than 1 centimeter during the period between neap tide and the following spring tide. The fact that on neither beach was there an increase in thickness of the layer of cavernous sand during the several days preceding spring tide may be due to the presence of another factor: the prevalence of deposition or erosion of sand during intermediate parts of the bi-weekly tidal cycle, as discussed by Shepard and La-Fond (1940).

GEOLOGICAL SIGNIFICANCE

Features developed by air entrapped in the sand have several possible geological applications:

1. Sand holes and sand domes can serve as criteria of the true order of deposition for steeply inclined or vertical beds of sandstone. The sand holes are likely to be filled by sand and may not be easily recognizable. However, similar holes have been discovered in the Cambrian Tapeats sandstone of the Grand Canyon (E. D. McKee—personal communication). Truncated sand domes formed in laminated sand should be even more easily recognized, either in sections across the bedding (pl. 2, fig. 1) or parallel to the bedding (pl. 2, fig. 2). They are probably also more likely to be preserved than swash marks, which have been reported in ancient sandstones (Clarke, 1918), A similar geological role

as a criterion of the order of deposition has been assigned ripple marks (Twenhofel, 1932, pp. 665, 666) but on most beaches sand domes are far more abundant.

2. The greater abundance of the sand holes, sand dunes, and cavernous sand near the upper part of marine beaches is probably the result of the more complete drainage during low tide with consequent entrance of air which later becomes trapped as the tide again rises as discussed above. In lakes or other bodies of water having no tide and only small waves, drainage of beaches is less complete and the features should not be so abundant. Accordingly, an ancient sandstone containing an abundance of these features on most of the laminae was probably deposited as a marine beach. If the features are rare, or present on only a few laminae, they could have been formed during a storm, a seich, or a heavy rainfall on a lacustrine beach. The features are probably extremely rare in dune sands.

3. Kindle (1936) suggested that the cavernous sands may become layers containing abundant concretions developed because of the free circulation of ground water. Concretions, however, probably must form before the cavernous layer is deeply buried, because of the likelihood of compaction. This ease of compaction also renders unlikely his suggestion that the cavernous sands may become good oil and gas reservoirs.

4. Tracks made by an animal walking over cavernous sand may be very deep even though the animal be of relatively little weight. Moreover, it is even possible that tracks formed in ancient cavernous sands may later be shown as raised areas, because the original track depression is likely to be filled by non-cavernous sand which will be less compacted than surrounding cavernous sand by the weight of overlying beds.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 15, NO. 2, PP. 50–54
FIGS. 1–2, TABLE 1, AUGUST, 1945

TRIASSIC SEDIMENTS IN WEST TEXAS AND EASTERN NEW MEXICO

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ABSTRACT

Triassic deposits in West Texas and eastern New Mexico are divided into three formations: Tecovas, Santa Rosa, and Chinle. Identification, correlation and derivation of the sediments in each formation were determined by sedimentary characteristics. These characteristics involve heavy mineral suites, physical and optical properties of minerals, degree of abrasion, textural range, inclusions, and degree of alteration.

INTRODUCTION

Triassic sediments occur in discontinuous outcrops extending from Pecos River Valley near the town of Santa Ross eastward along Canadian River Valley from Logan to Amarillo, then southward to Palo Duro Canyon and the area adjoining the eastern edge of High Plains. Using sedimentational methods, materials in all outcrops reveal characteristics by which correlation of the formations and the probable source of the sediments can be determined.

Triassic deposits in West Texas and eastern New Mexico, generally known as "Dockum Beds," have been subdivided by Darton, Adams, Gould and others into three formations which, in ascending order, are Tecovas, Santa Rosa, and Chinle. The Tecovas formation, named by Gould from a section in Tecovas Canyon, is exposed in Palo Duro Canyon and the Canadian River Valley. It consists of vari-colored, calcareous shales and gray sandstone lenses, which, as described by Atkins, attain a maximum thickness of 850 feet in Palo Duro Canyon and 115 feet in the Canadian River Valley.

The Santa Rosa sandstone, probably equivalent to the Trujillo formation of Gould's classification, was named from an exposure in a railroad cut near the town of Santa Rosa. This sandstone is compact, cross-laminated, vari-colored and in the type section attains a thickness of approximately 70 feet. In the exposure near Santa Rosa two thin conglomerate layers are present; one is about 15 feet from the base and contains clay balls; the other is about 25 feet from the top at the base of a compact sandstone layer. This formation in the Canadian River Valley near the town of Logan is similar to type section, but in Palo Duro Canyon and north and west of Amarillo in the Canadian River Valley, it consists of three to five sandstone ledges separated by red shales.

The upper Triassic Chinle formation outcrops in two widely separated areas; one near the town of Montoya; the other fringes the High Plains to the east and southeast. This formation has a maximum thickness of about 250 feet and consists primarily of red shales with interbedded lenses of gray and red sandstones.

METHOD OF PROCEDURE

Samples collected from exposures at Santa Rosa, Montoya, Logan, in Canadian River Valley, in Palo Duro Canyon, and in the area fringing the eastern margin of High Plains, represent as nearly as possible a cross section of the deposits. In the laboratory 50 grams of materials from each sample were sieved to determine the textural range. The heavy minerals of specific gravity greater than 2.6 were removed by bromoform from each size grade. After the frequency of the individual heavy minerals, recorded in percentages, was obtained by grain counts from materials in each collected sample, the percentages for the formation were computed by adding together the

frequencies of each mineral and dividing by the number of samples. Degree of abrasion, expressed in per cent of rounded, sub-rounded, sub-angular, and angular grains were secured by using the $\frac{1}{16}$–$\frac{1}{8}$ size grade.

The heavy minerals and inclusions, degree of abrasion, and mechanical analyses serve to identify the Tecovas formation. The heavy mineral suite consists of an abundance of tourmaline and zircon; a small per cent of magnetite, ilmenite,

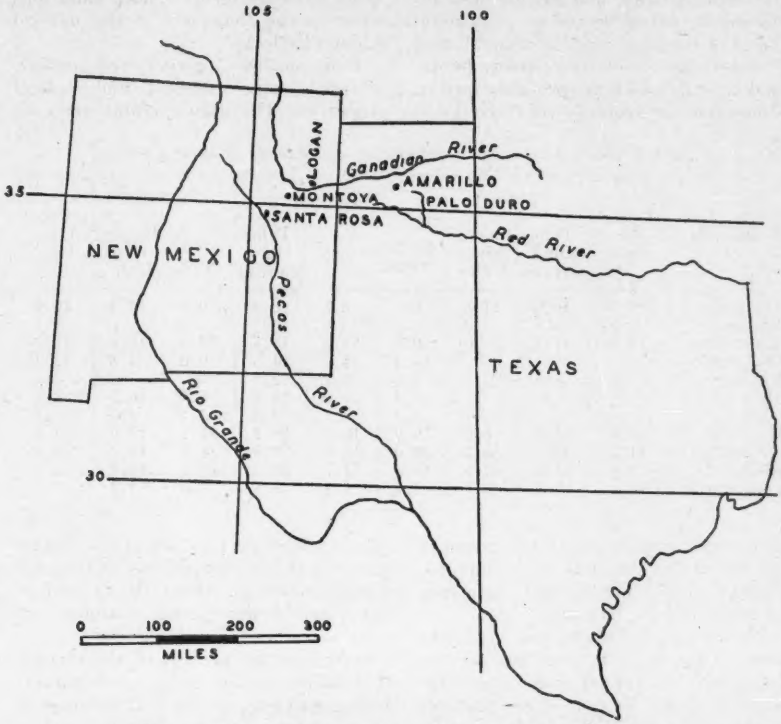

FIG. 1.—Map showing general location of Triassic outcrops

MINERAL AND PHYSICAL ANALYSES

Sedimentational analysis of the materials secured from each outcrop studied involved: identification of the minerals, type and arrangement of inclusions, textural range of the sediments, degree of mineral alteration, and the outstanding physical and optical properties of the minerals. These criteria permitted correlation of the exposures and determination of the probable derivation of the sediments.

rutile, and leucoxene; and a few grains of epidote (table 1).

The degree of abrasion was determined from quartz, tourmaline, and zircon. As shown by these minerals the degree of abrasion is one of the chief distinguishing characteristics of the Tecovas sand grains and they differ from the overlying sediments in three respects: abundance of rounded grains, limited number of angular fragments, and paucity of euhedral grains (fig. 2).

Three minerals in the Tecovas formation, quartz, tourmaline, and zircon, contain inclusions. The quartz grains contain three types of inclusions which are transparent crystals with index of refraction higher than quartz, small, dark colored dust-like particles, and gas gubbles. Inclusions in tourmaline consist of an abundance of irregular, opaque minerals and a minor number of transparent, hexagonal crystals which are probably quartz. Zircon contains inclusions of three types:

Compared to Tecovas formation the heavy mineral suite exhibits several major differences. One is the introduction of garnet, mica (only magnetic mica considered), and chloritic matter. Second, the mineral ilmenite was not noted in Santa Rosa sediments. Third, variations occur in the frequency of the mineral grains (Table 1).

Two minerals, garnet and quartz, possess unique physical and optical properties. The garnet grains are con-

TABLE 1. *Heavy mineral suite, per cent of total number of mineral grains.*

Minerals	Upper Permian	Tecovas		Santa Rosa			Chinle		Pre-Cambrian
		Palo Duro Canyon	Canad. River Valley	Santa Rosa	Logan	Palo Duro Canyon	Montoya	Eastern High Plains	
Magnetite	9.6	10.0	11.8	6.4	6.5	6.3	9.9	14.4	10.4
Ilmenite	9.2	10.5	9.0						1.1
Tourmaline	18.9	17.7	24.0	19.8	19.8	18.7	13.3	18.0	18.3
Garnet				14.4	14.7	14.3	9.0	4.8	12.2
Epidote	.7	.6		2.0	2.1	2.3			2.1
Mica				7.3	7.0	6.4	6.4	10.9	8.9
Chloritic				3.2	3.7	3.3	3.4	4.7	2.5
Hematite	8.4	7.2	6.6	9.9	10.8	10.4	15.1	13.9	9.4
Zircon	34.2	33.4	34.7	20.0	18.9	20.3	24.5	16.2	20.5
Rutile	12.6	13.6	10.2	14.3	14.7	14.5	16.4	14.8	14.6
Leucoxene	6.4	7.0	3.7	2.7	1.8	3.5	2.0	2.3	

elongated, transparent crystals arranged parallel to the long axis of the mineral, small zircon crystals, and numerous spherical, opaque minerals.

Particles in the shales and sandstone lenses of the Tecovas formation are distinguished by limited size range. Approximately 65 per cent of the particles in the shales are less than $\frac{1}{64}$ mm. in diameter; practically all the sand grains in the sandstone lenses fall in the size grades between $\frac{1}{16}$ and $\frac{1}{4}$ mm. in diameter.

Significant criteria for correlation of Santa Rosa formation include: heavy mineral suite, inclusions, mineral properties, and degree of abrasion. By utilizing these characteristics this formation can be traced from the section in Pecos River Valley eastward as far as Palo Duro Canyon. Though the materials in the easternmost outcrops reveal minor variations they are strikingly similar to the type Santa Rosa.

spicuous because they are almost transparent and have spotted and rectangular surface markings. About 10 per cent of the quartz grains disclose undulose extinction and crenulated borders.

Inclusions are present in the quartz, tourmaline, zircon, mica, and garnet. Inclusions in the quartz grains consist of an abundance of gas bubbles and a limited number of acicular minerals which are probably rutile. Two types of inclusions are present in magnetic mica. These are opaque minerals, probably iron oxide, and small crystals of garnet, zircon, and rutile. Opaque mineral inclusions were encountered in a limited number of garnet grains. Inclusions consisting of rod shaped crystals and large gas bubbles are conspicuous in the zircon.

The Santa Rosa sediments are distinguished from those of the Tecovas formation by angularity of sand grains and abundance of euhedral grains. Maxi-

mum angularity for all minerals reaching a high of approximately 60 per cent in the quartz, is attained in the deposits near Logan. Both east and west of this area in the exposures at Santa Rosa and Palo Duro Canyon, decrease in angular

Mineral content and presence of particles of bentonitic clay identify the Chinle deposits. Compared to the Santa Rosa formation the heavy mineral suite differs chiefly in the abundance and properties of individual minerals. Magnetite and

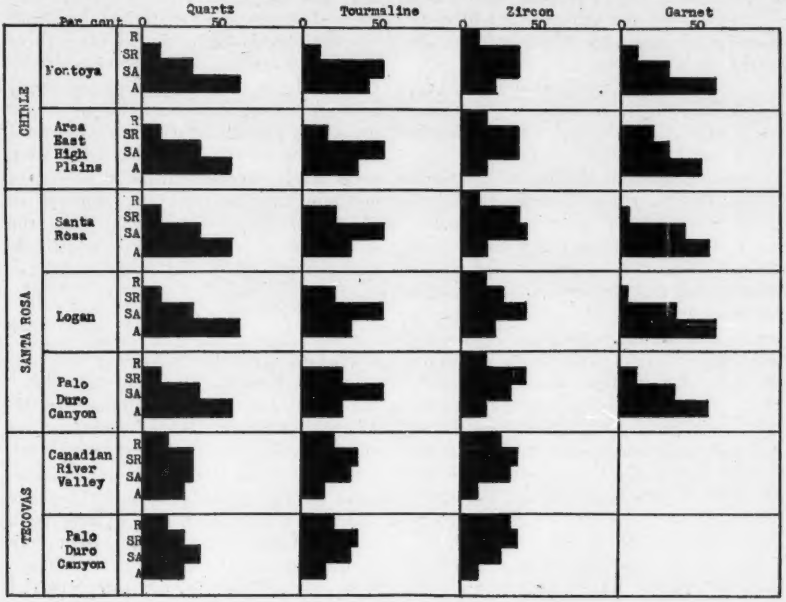

FIG. 2.—Abrasional wear of the minerals, per cent of rounded, sub-rounded, sub-angular, and angular grains

particles corresponds to an increase in sub-angular and sub-rounded grains. About two-fifths of the tourmaline and zircon grains are euhedral.

It was anticipated that the Chinle formation would show variations in exposures approximately 150 miles apart, yet the sediments have remarkably similar characteristics. The sediments contain the same heavy minerals but they differ in abundance. Extensive mineral alteration, especially in the mica, and increase in abundance of well abraded grains is more apparent in the outcrops adjoining the southeastern rim of the High Plains.

hematite show a substantial increase. Garnet particles are less common. They have darker colors, more inconspicuous surface markings, and more rounded grains than in the Santa Rosa formation.

Disseminated through the shales are white and gray bentonitic particles composed of montmorillonite. Some are fragmental and can be deflocculated only after crushing. Others are soft and respond to bentonite tests.

SOURCE OF SEDIMENTS

The evidence indicates that the materials of the Triassic deposits were de-

rived from three probable sources. Fragments from the underlying Permian in the Tecovas formation supports Adams' conclusion that the Tecovas sediments were derived chiefly from reworked Permian materials. Additional evidence confirming this derivation is the similarity of Triassic and Permian sediments. Practically all the criteria that identify Tecovas deposits are applicable to the upper Permian.

Introduction of new minerals, garnet and mica, and the abundance of angular sand grains is evidence that a source other than the known Permian contributed materials during middle and upper Triassic times. Nearby Pre-Cambrian outcrops of igneous and metamorphic rocks in southern Sangre de Cristo Mountains are suggested as sources. Several factors substantiate this suggestion. Practically all criteria which serve to identify Santa Rosa sediments are applicable to deposits in tributary valleys of Canadian River, especially the tributaries that are largely within the confines of Pre-Cambrian outcrops. Physical and optical properties of the minerals in the Santa Rosa formation and the tributary valley deposits are strikingly similar. Some of the outstanding properties found in the minerals of both deposits include: garnet grains are almost transparent and have the same spotted and rectangular surface markings; percentages in respect to abundance of mauve and transparent zircon grains are practically the same; type and arrangement of inclusions in each of the minerals zircon, quartz, tourmaline, garnet, and magnetic mica are almost identical; and strain shadows and crenulated borders are present in approximately 12 per cent of the quartz grains.

The same source probably prevailed from the middle into the upper Triassic but this supply was no doubt supplemented by reworked materials. Evidence supporting this suggestion involves three factors; limited deviation in characteristics of Chinle and Santa Rosa sediments indicate a continuation of the same supply which provided the Santa Rosa sediments; bentonitic clay particles were very likely derived from deposits of volcanic clastics; and the increase in degree of abrasion, especially in the eastermost deposits, denotes additional transportation.

SUMMARY

Variation in the sediments are sufficient to distinguish each of the formations. Differences in the sediments of the Tecovas and Santa Rosa formations are more apparent than the differences between the Santa Rosa and Chinle formations. Three probable sources for the materials are implied. The sediments in Tecovas formation were derived largely from reworked Permian, but the Santa Rosa and Chinle formations received sediments which seem to have been derived from igneous and metamorphic rocks. During Chinle time a supplementary source consisting of volcanic clastics probably existed.

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FIGS. 1–2, AUGUST, 1945

CALCITE OOLITES OR "CAVE PEARLS" FOUND IN THE "CAVE OF THE MOUNDS"

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ABSTRACT

Small oolites or "cave pearls" found in a cave in the upper part of the Galena formation are described. The oolites are of lenticular shapes and range in diameter from 2.4 to 4.4 mm. They were found in a small cavity on the wall of the cave. Some oolites were free in the bottom of the cavity; others were attached to the bottom.

Calcite oolites or "cave pearls" were found in the CAVE OF THE MOUNDS, a newly discovered limestone cavern a mile east of Blue Mound, Wisconsin. Blue Mound is an outlier of the Niagara limestone, which are so extensively developed in eastern Wisconsin. This limestone at one time covered the entire southern half of the state and may have extended over the entire state. The summit of Blue Mound with elevation of 1716 feet above sea level is the highest elevation in southern Wisconsin. It is capped by around 150 feet of the Niagara limestone which at this place has very largely been replaced by flint. Blue Mound is about 30 miles west of Madison, Wisconsin, in the Driftless Area of southwestern Wisconsin. The cavern, which has no natural entrance, was discovered August 4, 1939, while road contracters were getting Galena limestone from the quarry on the C. I. Brigham farm. Geologists from the University of Wisconsin and the University of Chicago had long used the quarry for study on student field trips and it was included as a stop on the itinerary of the Kansas Geological Society 1935 Ninth Annual Field Conference (pp. 121 and 421 of the Guidebook of that trip). The rock exposed in the quarry and in which the cave had been developed is a part of the Galena formation of the Ordovician system.

"Cave of the Mounds" was opened to the public May 30, 1940. During the summer, Guide Larry Burns, a geology student in Beloit College, carefully examined sections of the cave wall with a flashlight. In a small solution cavity on the west wall of the South Cave he found a "nest" of a dozen free oolites (fig. 1. Oolites shown *in situ* behind a magnifying glass.)

The depression or "nest" in which the oolites rest is about 2.3 centimeters in diameter and is part of a larger cavity 10.5 cm. long, 6 cm. wide and 15 cm. high. The floor of this smaller depression is paved with at least 25 oolites which have coalesced or joined together.

The free oolites range in size (see attached table) between the limits of 2.1 and 4.4 mm. in diameter. In shape they are lenticular, spherical or cylindrical. Five show slight depressions as if they had rested against others while forming. Number 12 has a distinct pit of this nature.

Through the courtesy of Dr. Twenhofel at the University of Wisconsin, one of the Cave of the Mounds oolites was sectioned (fig. 2). The section shows 54 recognizable concentric layers about a central nucleus consisting of a grain of sand which is not quite round but approaches egg-shape.

Distinct radial structure is visible about the center through at least fourteen layers. Farther out they can be seen at different places through two to six layers.

The layers are very nearly uniform in thickness and follow the outline of the nucleus. To the upper left (about 10 o'clock position) about thirty-three layers from the nucleus a dark layer shows some thickening causing the succeeding light

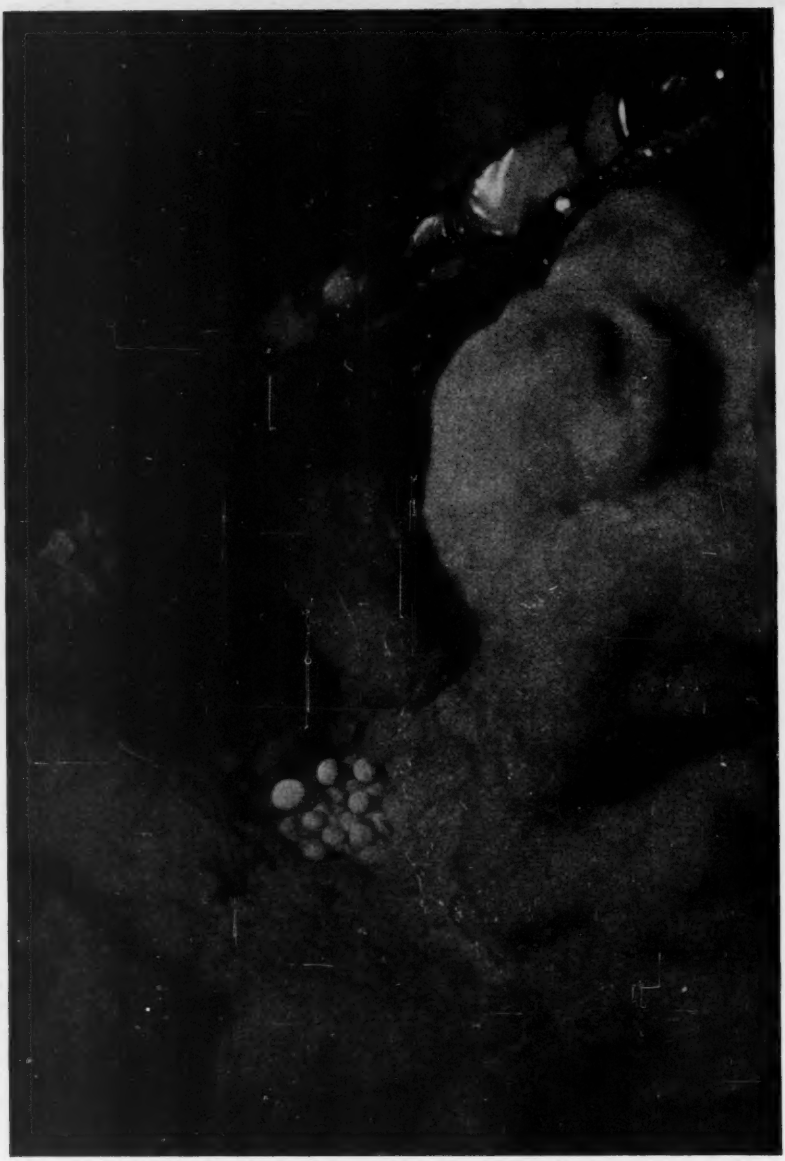

FIG. 1.—Free oolites *in situ* in a solution pocket, south wall, "Cave of the Mounds," as seen through a magnifying glass. Photograph by Alonzo W. Pond, Cave of the Mounds, Blue Mounds, Wis.

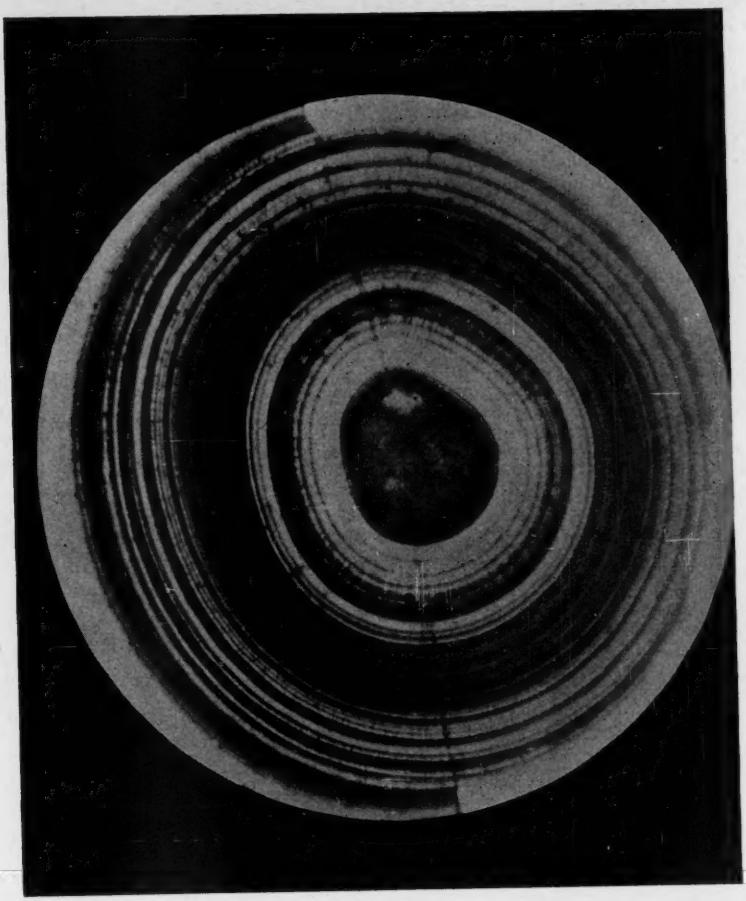

FIG. 2.—Cross section of oolite from "Cave of the Mounds." About 60 times natural size. Photograph by University of Wisconsin.

layers to bulge away from the nuclear outline. Still farther out is a wide, dark layer. Following this counter clockwise, it breaks into two dark and one light layers. These remain distinctly separate around to the top of the photograph.

Cave pearls, or cave oolites, are not common. According to Casteret, a cave explorer in Europe, they are "the ultimate rarity in cave formations." In this country "cave pearls" have been found free in Carlsbad Caverns, New Mexico (Hess); Cathedral Cave in Missouri (Keller); and a cave in Idaho (Mackin). At Howe Caverns, New York, some almost free oolites, but actually attached to a slab of calcite, are on exhibition in the cave house lobby.

DIMENSIONS AND SHAPES OF THE "CAVE OF THE MOUNDS" OOLITES

1. 4.4 mm. ×3.2 mm. Lenticular
2. 4.1 mm. ×3.2 mm. Bean or cylinder
3. 3.5 mm. ×2.7 mm. Lenticular
4. 3.0 mm. ×2.3 mm. Lenticular
5. 3.1 mm. ×2.7 mm. Bean
6. 2.8 mm. ×2.2 mm. Cylinder
7. 3.1 mm. ×2.5 mm. Lenticular
8. 2.7 mm. ×2.3 mm. Asymmetrical round
9. 2.8 mm. ×2.1 mm. Cylindrical
10. 2.5 mm. ×2.3 mm. Asymmetrical cylindrical
11. 2.2 mm. ×2.1 mm. Square (round corners)
12. 2.8 mm. ×2.1 mm. Pitted, round

Five of these show slight depression.

Cavity or "nest" is 2.3 centimeters in diameter. Main cavity is 10.5 cm. ×6 cm. wide ×15 cm. high.

At least 25 oolites are cemented to the bottom.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 15, NO. 2, PP. 59–71
AUGUST, 1945

THE ROUNDING OF SAND GRAINS

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ABSTRACT

Important literature relating to the rounding of sand grains is reviewed with comments. Methods of transportation of sands in suspension and traction are examined and it is stated that suspension transportation in either water or wind is not effective in producing rounding of transported particles. Aqueous transportation by traction is considered for streams and on beaches and eolian transportation in any environment. It is concluded that stream traction transportation does not favor rounding of sand grains, that wave traction transportation is not very if at all effective in producing rounding on sands of the specific gravity, solubility, and hardness of quartz on grains less than ¼ mm. in diameter and is not very effective on grains in the ¼ to ½ mm. grade, is considerably effective on grains in the ½ to 1 mm. grade, and increasingly effective with increase in dimension. Rounding by wave traction transportation is readily produced on minerals of high specific gravity as magnetite and zircon to dimensions as small as $\frac{1}{16}$ mm. in diameter, and that any rounding of sand grains by aqueous traction transportation requires travel of many thousands of miles. It is concluded that eolian traction transportation is more effective in producing rounding than aqueous traction transportation for the same distance traveled, and that grains less than ¼ mm. in diameter of the hardness and specific gravity of quartz may be rounded in such transportation. Eolian traction transportation can produce frosted surfaces on grains less than 1 mm. in diameter. Aqueous traction transportation can not produce frosted surfaces on grains less than 1 mm. in diameter, rarely produces such surfaces on grains in the 1 to 2 mm. grade, and readily does so on grains larger than 2 mm. and to higher degrees with increase in dimension. It is insisted that most sand assemblages are composed of grains with extremely varied and often complex histories, and that these histories must be considered in any examination of sands for discovery of facts of sedimentational significance.

INTRODUCTION

Considerable has been written relating to the rounding of sand grains. It seems to have been generally conceded that this is more effectively done and to smaller dimensions by wind transportation than by water transportation, but from time to time this generalization has been challenged. Wind and water carry particles of sand dimension in the two ways of suspension and traction. In the method of transportation in suspension the particles are suspended in the medium and in traction transportation the movement is by rolling over the surface or in a succession of jumps. The writer is of the opinion that very little rounding is accomplished while particles are in suspension and that essentially all rounding and development of sphericity which are not primary, that is, developed when the grains were first formed, is due to transportation by traction, particularly rolling, whereby corners are abraded. He is led to this view by observation of the results of aqueous transportation over many hundred of miles of sea beaches, transportation of sands by wind over the back beaches and adjacent shore dunes over a somewhat equal distance, by studies of the movement of sands in streams, on a stream table, and studies of sands collected on many parts of the Atlantic and Pacific shores of North America, on Hudson Bay, islands of the East and West Indies, the Hawaiian Islands, from the Sahara Desert, the deserts of California, New Mexico, Arizona, and the Desert of Gobi. These observations have extended over more than three decades. The generalizations which are made in this paper apply to particles less than ½ mm. in diameter. Development of rounding and sphericity on particles larger than ½ mm. in diameter

is easily understood and several very excellent laboratory studies have been made of particles of pebble dimension.

Any generalizations made respecting the development of rounding and sphericity from collections of sands from dunes, beaches, and streams, in general, have very little value as there is little possibility of determining previous histories of the sands collected. This is shown by the following example from Coos Bay on the coast of Oregon. At the entrance of Coos Bay from the sea there is a long and wide sand spit which has been extended southward from the north entrance of the Bay. Dunes cover the surface of the spit. The seaward side of the spit has a broad, gently graded fore beach and also a wide back beach. The sands on the fore beach are washed back and forth by the waves, at times moving south, at other times north. At low tide the sands above low tide level become dry and some are shifted by the wind to the back beach and some to the dunes over the spit. Sands also move at times from the dunes to the back beach and from the back beach to the fore beach. Configuration of the shore very frequently leads to winds of low velocity becoming concentrated to produce winds of much higher velocities. The winds frequently carry sands into Coos Bay from which tidal currents may return them to the sea. Any effects of rounding and sphericity produced on sands in the neighborhood of the Coos Bay spit are due to both wind and water transportation and there is no known way of determining from these sands the degree of responsibility. If a sample of highly spherical and well rounded sands is collected on the ocean beach at Coos Bay, there is no justification whatever for referring the roundness and sphericity to aqueous transportation. The same statement may be made for any sample collected from a dune on the spit and, even if the grains from the spit are frosted it does not follow that this was produced by wind transportation as the frosting may have been developed long before the grains were acquired by wind. As a matter of fact, any rounding of sands collected at either place may not be due at all to aqueous transportation on the seashore at Coos Bay or to eolian transportation on the Coos Bay spit, as the grains may have been rounded long before they arrived at these places. The problem is further complicated by selective transportation. Suspension transportation moves angular grains of a given weight and specific gravity in advance of spherical grains of the same weight and specific gravity and sand grains composed of minerals of low density in suspension transportation outrun sands of the same volume composed of minerals of high density. In traction transportation large spherical grains of sand advance faster than small grains of the same specific gravity, and grains of high sphericity outrun angular grains of the same volume. The selective transportation leads to concentration of grains of a high degree of rounding and sphericity at some places and of a high degree of angularity at others. The highly spherical grains may be rolled inland from a beach to a dune, thus giving the impression that dune sands are highly spherical and well rounded in spite of the fact that wind transportation may have had little or nothing to do with the rounding, most of the transportation leading to the rounding perhaps, having been done by aqueous transportation on a beach.

REVIEW OF THE LITERATURE

Daubrée, Mackie, Goodchild, and Ziegler were among the first who considered the rounding of sand grains, and the formulas of Mackie and Ziegler seem to show that they considered the development of rounding to have been produced by traction transportation although Ziegler's experimental work placed the grains in suspension. Both pointed out that rounding is more effectively done by wind transportation because of the cushioning effect of films of water on the grains and the inertia and viscosity of

water as compared to air, and both stated that little abrasion of small grains is done in water because of the difficulty of the small grains coming in contact with sufficient force to abrade. Water also decreases the effectiveness of contact because of decrease in specific gravity of an object suspended therein. Ziegler expressed the opinion that particles less than $\frac{1}{4}$ mm. in diameter could not be rounded in water. Daubrée in 1879 had stated that particles less than $\frac{1}{10}$ mm. in diameter could not be rounded in water. Ziegler also stated that well rounded grains of $\frac{1}{4}$ mm. or smaller dimension appear to result from abrasion due to eolian transportation. Since Ziegler's experimental work was done by dropping grains down long glass tubes filled with liquids of different viscosities and the particles were in suspension, there seems little basis for any generalization made as a result of these experiments as having application to aqueous traction transportation. Goodchild (p. 211) stated "We may conclude with a tolerable amount of certainty that any sandstone largely composed of well-rounded grains of sand, represents a desert sand and was formed under arid conditions, on a land surface." Goodchild considered dimension and called attention to the difficulty of abrasion with decrease in dimension of particles, but the generalization stated in the quotation is altogether too far-reaching. If the grains are $\frac{1}{2}$ mm. in diameter or greater dimension the sand grains may have been produced by aqueous transportation and the deposition made by the same agent.

Knight used sands composed of quartz and having dimensions of 1 to 2 mm. in diameter. These were placed in the form of a dune on an endless belt with a wind current of about 40 miles per hour with movement of the belt at a rate so that the dune held a constant position on the belt with respect to the entire apparatus. He was able to reduce 34.5 per cent of the grains to less than $\frac{1}{2}$ mm. in diameter in 50 miles of travel. In a travel of this distance a sand grain 1 mm. in diameter would have been rolled over somewhat more than 25,000,000 times. Knight's experimental work shows the effectiveness of wind transportation in abrasion, reduction in size, and rounding.

Galloway investigated the possibility of sand grains becoming rounded by solution and he considered this a factor of some importance. It probably is important on calcareous sands and other sands composed of minerals of low solubility, but it also seems probable that it has not a great deal of significance on quartz sands and as these compose most sands it is thought that solution as a factor in the rounding of quartz grains may be dismissed as improbable. Some of the Cambrian sandstones of the upper Mississippi Valley have had water passing through them for millions of years and many of these possess a high degree of angularity. Galloway found that grains of quartzite, dolomite, mica and hornblende could be rounded down to $\frac{1}{16}$ mm. in diameter by mutual abrasion in water in 50 hours of travel at the rate of 4 miles per hour, that the lower effective limit by abrasion in water is $\frac{1}{256}$ mm. and that the rate of rounding becomes progressively slower after the grains are reduced to a diameter of about $\frac{1}{4}$ mm. and below that dimension the time required to round sand grains is very long. The smallest spherical grain of quartz he was able to produce in 150 hours of travel at the rate of 4 miles per hour had a diameter of $\frac{1}{8}$ mm.

Kindle pointed out that some rounding of sand grains may be accomplished in the intestinal tracts of organisms of which some devour large quantities of sand and mud for the contained organic matter. The writer considers this a real agent in producing rounding as the muscles moving the intestinal tracts force the grains in contact and also rotate them. One may observe the effects of rounding of grains in this way by examination of the rounded grains in the gizzards of chickens and other barnyard fowls. Although this method of rounding may have great

quantitative importance over some parts of the sea bottom, it is believed that it has little application to the sand of beaches and certainly none to the sands of dunes.

Galloway (1922) stated that if sand grains are noncalcareous and have more than 50 per cent rounded, "the sand is eolian." If deposition is meant, this is a very inaccurate generalization. The percentage of rounded grains in a deposit is not particularly important as a criterion of the agent and environment of deposition. Wind may blow highly rounded grains into a lake, the sea, or a stream and the water may deposit these grains with sands which never felt the effects of eolian deposition. After deposition, over 50 per cent of the grains may have a high degree of rounding, have a high degree of sphericity, and may also have frosted surfaces, but the deposit is not one of eolian deposition. The frosted grains, if less than $\frac{1}{2}$ mm. in diameter testify to eolian transportation, but do not prove eolian deposition. Characters in the deposit other than rounding and frosted surfaces must be used to determine the environment of deposition. Galloway (1922) makes one observation which with qualification as to diameters is believed by the writer to be sound and that is "Wind-abraded grains are frosted like ground glass; water-abraded grains are polished and glassy." This applies if the grains are less than $\frac{1}{2}$ mm. in diameter.

Anderson's studies led him to the conclusion that traction and not suspension transportation is responsible for the development of rounded grains—a conclusion with which the writer is in complete agreement—that the rounding of sand grains by mechanical wear is an extremely slow process—also a conclusion strongly endorsed—that water is a more effective agency in rounding beach and dune sands than is wind when it rolls dry sand over the same distance—a very questionable conclusion—and "From the slow rate of reduction which has taken place, it does not appear likely that sand grains in a single journey from the central part of a continent to the sea would experience sufficient wear to become rounded. In order to become rounded either by wind or water, sand grains would probably make several such journeys, through more than one cycle of erosion, transportation and deposition" and "It follows that sand grains approaching spherical shape may be of considerable age. No such grains should be regarded as having been derived from their primary source, the igneous rocks, during the present cycle of erosion." With these general conclusions the writer is in accord except as noted. Anderson was led to his view of the effectiveness of aqueous abrasion as compared to that produced in wind transportation because of the facts that wind must have a considerable greater velocity to move sand of a given dimension than a current of water, that wind is handicapped because its velocity adjacent to the ground is generally much less than at higher levels, that in a dune only the top sands are those moved, and that the sands beneath the surface remain stationary over long periods of time. However, velocities of wind are generally several times greater than the velocities of water and while velocities adjacent to the ground are generally lower than those at higher levels, these velocities are usually adequate to move fine sands and in places conditions are such as to produce velocities which are actually very high. If the trips from the center of a continent to the sea are made in streams of considerable velocity, the chances of rounding are very slight, no matter how many trips are made as the transportation of the fine sands would be in suspension with no rounding accomplished and any coarse sands carried by traction would move with gravels under which conditions the sands would be broken, or as stated by Marshall for beaches, sands under these conditions "can not live on a beach where wave action keeps gravel in movement." It is the writer's opinion that little rounding of fine grains is done in streams,

particularly, those with fast water. The view expressed by Anderson that rounding is more rapidly done in water than in air is seriously questioned. Anderson states that beaches are the ideal places for development of rounding and he minimizes the ability of the wind to effectively round grains for the reasons stated above. Relative to Anderson's statement that only the top sands of a dune are moved, the same comment may be made for the sands of beaches in that only the sands on the surface experience much movement. Those below the surface are stationary for long periods of time, whereas the sands of the back beach are more or less constantly being moved by the wind and the area over which this takes place not uncommonly exceeds that over which waves move sands. In arid regions with limited quantities of sands they are almost constantly in motion. It is only where dunes are large that the resting stages are long. Anderson also notes that the rounded grains in a deposit are a consequence of selective sorting and if only a part of a deposit is examined a very incorrect picture of the entire deposit may be obtained.

MacCarthy's studies of the rounding of beach sands led to a view in some respects like that of Anderson with respect to rounding and he found that no evidence of rounding developed on grains during a straight line transportation of 130 miles on a beach, but with the actual distance of travel unquestionably much greater. He also noted that apparent rounding is a result of selective sorting and that grains after travel on a beach seem to become more angular and that well rounded grains have a long history behind them. MacCarthy stated that eolian sands are much rounder than beach sands and that beach dune sands appear much rounder than the sands of desert dunes. The writer sees no basis for the latter part of the statement.

Russell and Taylor studied sands collected on the Mississippi River and expressed the view that rounding of sand grains is customarily not done in streams, if the sands of the Mississippi River are representative, since they found that angularity of grains increased with progress down stream. They referred the decrease to the grinding and breaking of sand grains between particles larger than sand size. This may be the explanation, but the increase in angularity may also be due to selective transportation which led to the angular grains outrunning the more rounded ones, particularly if the transportation was in suspension. This effect might not take place in streams in which sands were the largest particles carried. Krynine expressed disagreement with the general conclusions of Russell and Taylor as to the absence of much rounding of sand grains in streams and stated that he had observed rounding of sand grains in some streams in New England, Pennsylvania, and in the Himalaya Mountains and he states that "in the initial stage the passage from angularity to subangularity is accomplished in a very short period." This statement is not in accord with results obtained from laboratory treatment of sands or with the observations of the writer. Krynine does not state how he determined the rounding was done in streams and before accepting his conclusion relative to rounding of sand grains in streams one should have the entire history of the grains of sand observed by him in the New England, Pennsylvanian and Himalayan streams from the times of detachment from the primary parent rocks to the times of observation. If the grains were derived from sedimentary rocks, they may have had several stages of rounding before entrance into these rocks. Unless Krynine knew the sources of the sands observed by him or actually studied the sands from the beginning to the end of transportation, it is somewhat uncertain how he knows that rounding took place. Finding rounded grains in a stream proves nothing except that the grains were in the stream and were rounded. Finding angular grains in

a stream proves either that the conditions in a stream are not such as to promote rounding, or that the extent of transportation has not been long enough to produce rounding.

Russell in a rather comprehensive consideration of the "Effects of transportation on sedimentary particles" stated that many current views affecting sand grains do not seem to be correct and that the most favorable sites for rounding of sand grains are places of great sand concentration, particularly on beaches or in dunes (1939). It is questionable if great sand concentration is where rounding is most effectively done.

What seems to be the most thoroughgoing investigation to determine the extent of transportation to produce rounding of sand grains was made by Thiel. He used quartz, microcline, apatite, hornblende, garnet, and tourmaline. The minerals were crushed to sand size and fragments passing a 9-mesh screen and held on the 16 and 32-mesh screens were used. These are of dimensions of ½ to 1 and 1 to 2 mm. The fragments were placed in a steel drum divided into two compartments by a partition parallel to the flat sides. The rotation of the drum was geared to a velocity of 25 revolution per minute at which speed the velocity of the inner surface of the drum traveled approximately 1.8 miles per hour. Apatite, microcline, and tourmaline were placed in one compartment of the drum and quartz, hornblende and garnet in the other. Twenty grams of each were used and the total 60 grams of each half were placed in 3 liters of water. The quantity of water was such that only the water adherent to the inner surface of the drum was carried through a complete revolution. The minerals were examined after travel of 2,000, 3,000 and 5,000 miles. After travel of 5,000 miles the quartz grains showed very little rounding and sphericity had increased in the 1 to 2 mm. grade from .72 to .79 and in the ½ to 1 mm. grade from, .71 to .72 according to the Wadell formula of $\phi = dc/Dc$ where ϕ is the degree of sphericity, dc the diameter of a circle equal in area to the area obrained when the grain rests on one of its larger faces and Dc is the diameter of the smallest circle that cirscribes the outline of the grain. Obviously the smaller particles of quartz were abraded to a much less degree than the larger ones and in the case of the ½ to 1 mm. grade the changes after 5,000 miles of travel were extremely small. If all the travel was by traction, each particle in the ½ to 1 mm. grade could have made of total over 2,500,000,000 revolutions. The least wear on the smallest grains is what should have been expected, since the smaller the particles the less effective are their contacts with each other and it is possible that the small particles did some of the travel in suspension when it is believed that little abrasion is accomplished. Of the six minerals used by Thiel, quartz showed the least wear, apatite the most.

Pettijohn and Lundahl's work on Lake Erie beach sands is partly, at least, based on the assumption that the transportation of the sands grains studied by them was in suspension and in considering the matter of selective transportation they definitely state that "Suspension transport is implied." These students found that the longer the transportation of sands on the Cedar Point Spit on the southern shore of Lake Erie the less round the grains seemed to become and they reach the conclusion that "it can safely be said that one cycle of sedimentation makes no appreciable modification of the size and shape of the grains and very little change in roundness." The writer thoroughly agrees with this conclusion so far as suspension transportation is concerned and grains are less than ½ mm. in diameter for any method of transportation in water. He is, moreover, of the opinion that no or very little abrasion or rounding is accomplished in suspension transportation in either air water. Pettijohn and Lundahl refer the decrease in rounding with distance traveled to selective transportation

whereby the angular grains traveled faster and farther in suspension than the spherical ones and so the spherical grains were left behind. This is a reasonable explanation.

STREAM TRANSPORTATION OF SANDS

Streams with considerable velocity transport gravels as well as sands, silts, and clays. The gravels are ordinarily transported by traction and among them sands mingle from time to time. These sands must be repeatedly fractured by impact and grinding. It is believed that under these conditions it is not possible for sand grains to become rounded. Small grains of sand in streams with fast water are transported in suspension and little to no abrasion and rounding are done. If velocities are not great, the bottoms of the stream channels are locally covered with mud among which are mingled the grains of sand and these deposits are moved only at times of flood when most sediments are in suspension. Little to no rounding is done if the sands are rolled by traction over the mud. It is only in streams that carry sand alone, as is the case in some of the streams draining the Cambrian sandstone areas of the upper Mississippi Valley where traction transportation of sand free from much gravel or much mud is possible. Here some of the sand grains would seem to have the possibility of becoming rounded. The distance of transportation of sands in such a stream can be no longer than the stream is long over the areas free from gravel and mud and it is probable that some of the transportation over the bottoms free from mud or gravel is in suspension. Another feature of stream transportation is the extremely wide variation in competency from place to place and from time to time resulting in that the sediments are usually not well sorted. Although there doubtlessly is selective transportation, it is believed that it is not sufficiently selective to separate rounded grains of small dimension from angular grains of the same dimension.

The general conditions of stream transportation of sands of small dimension sum up to the conclusion that a high degree of rounding does not seem probable as a result of stream transportation and little rounding is produced under most conditions. It seems that in streams of high velocity the general tendency instead of producing rounded grains is in the direction of increase in angularity of grains.

BEACH TRANSPORTATION OF SANDS

Processes on a beach are greatly different from those in streams. Waves wash on and off a beach with the waves rarely advancing on a beach normal to the trend of the beach. Intensity of wave movement varies from hour to hour. from day to day, and from season to season. There is also movement of water over shallow bottoms in some degree parallel with the movement of the waves. Transportation is selective so that gravel is left or placed on one part of a beach, sand on another, and silt and clay on another, each, in general, not interfering with the others except at times of great competency when waves are strong the sand grains of small and to some extent large dimensions are in suspension and may be deposited with gravels moved by traction. It is when the sand grains are transported by traction and the grains are rolled on the beach by the waves and roll back with the returning water that abrasion takes place. On each trip up and down the beach a sand grain travels from 10 to 20 or more feet. If a wave rolls on a beach every minute there is travel ranging from 600 to 1200 or more feet each hour, and from 1000 to 2000 or more miles each year. A few years of travel should be adequate to round small grains if it can be done by waves. However, it should be noted again that it is only the sands on the top that are moved to any great extent. The grains beneath the surface are not moved except in

times of storms. The fact that grains of quartz up to about 2 mm. are not frosted is considered to indicate that the contact between grains is inadequate to produce this effect although this feature is commonly present on granules (2 to 4 mm.) and larger particles moved by waves. Salt water has a higher specific gravity than fresh water and the small weights of the small grains of sand in comparison to their surfaces and the reduction in weight due to the higher specific gravity of the salt water greatly reduces the possibility of abrasion. It is believed that abrasion is almost infinitesimal after a grain becomes as small as $\frac{1}{2}$ mm. in diameter for particles of the specific gravity and hardness of quartz. It is the writer's considered opinion that angular particles of quartz of $\frac{1}{4}$ mm. or smaller diameter can not be rounded by abrasion on a sea beach. Particles of the specific gravity of zircon (4.7) and magnetite (5.1) can be rounded to $\frac{1}{16}$ mm.

The quartz sands brought by the Columbia River to the Pacific Ocean are almost entirely unrounded to any degree. They seem to have about the same degree of angularity that they must have had when released from the parent rocks. Dimensions are small and most are less than $\frac{1}{2}$ mm. in diameter. These sands have largely come from eastern Oregon and Washington, Idaho, by way of the Willamette River from southern Oregon and some were probably derived from Canada. This travel has effected no rounding of any significance. In the upper reaches of the streams which started the sands on their travels it is probable that there was much fracturing of grains and after the grains became small it is also probable that much transportation was in suspension. After reaching the sea the sands are drifted along the coast and sands of the past must have done likewise. They made an unknown number of passages to and from the coastal dunes and after southward travel of about 20 miles in a straight line, they reached the town of Seaside and the cape of Tillamook Head. They acquired very little rounding in this travel. In this travel they moved southward during the times of the northwest winds and northward during the times of southwest winds. The rate of advance southward is not known but if they advanced southward at an average rate of a mile a year—probably far more than the actual rate of advance—, it would have required 20 years to have gone from the mouth of the Columbia River to the north side of Tillamook Head. If also the sands moved up and down the beach 1000 miles each year, the total travel in the 20 years would have amounted to 20,000 miles during which each grain, if all the travel had been by traction, would have made about 10,000,000,000 revolutions. Either very little of the movement was done in traction transportation, or little rounding is done on small grains of quartz sands in traction transportation on a beach. It is believed that the latter is the case.

EOLIAN TRANSPORTATION OF SANDS

Sands transported by wind ordinarily move by traction and only the surface parts of a deposit are affected and as Anderson has stated, a long time is required to move all the sands of a large dune and the extent of travel of each grain is not large. But many dunes are not large and the sands are often moved and in deserts the movement extends over long periods of time. The grains move in air and there is no reduction of weight due to the buoyant effects of the air. In deserts the movements extend over long periods of time. The effective force of contact is that of the specific gravity of the materials which for quartz is 2.7 instead of the 1.7 or less in water. The fact that fine-grained sands transported for a long time by wind seem to be always frosted proves the effectiveness of contact. Transportation, of course, is selective, but no gravels travel in company to produce fracture and it is not likely that contact between sands can

bring this about. Spherical grains roll more readily than angular and would be removed and concentrated in the leeward dunes. The writer is convinced that for the same extent of travel, rounding of small grains is much more effectively done in eolian transportation than in transportation by any other agent and he also doubts that rounding of small grain of quartz is produced in any form of aqueous transportation unless it is done by solution, and that is considered extremely improbable.

DEVELOPMENT OF FROSTED SURFACE ON SAND GRAINS

It has been generally considered and repeatedly stated that a frosted surface on sand grains is produced by eolian transportation. If this statement is qualified to the extent of stating that the grains with such surface are less than 2 mm. in diameter, the generalization is considered correct, but if grains larger than 2 mm. are included it very decidedly is not correct. A frosted surface can be observed on grains composed of all kinds of minerals transported on beaches if the grains are larger than 2 mm. in diameter and nearly every granule and larger particles of beaches have such a surface. Most people have collected wet pebbles with beautiful shiny surfaces and were disappointed to discover that when the particles became dry the shininess had disappeared and the surfaces were dull. This feature is frequently seen on pebbles containing fossils which are plainly visible when the pebbles are wet, but hardly show when the pebbles are dry.

But frosting is not developed on fine- and medium-grained quartz sands of beaches. The writer has examined sands of these dimensions over many miles of sea beaches and has yet to find any aggregate composed of frosted grains in quantity. Larger particles commonly show this feature and it is possible to find a few frosted particles in many aggregates of fine- to medium-grained sands, but the presence of these is easily explained as having been brought to the beach by wind. When frosted grains of quartz of fine- and medium-grained dimensions are found in quantity, they are found in dunes. This should not be interpreted as suggesting that all dunes are composed of frosted grains as such is not the case. Most seashore dunes which have been studied by the writer do not contain many frosted grains. The fact that dunes are places where frosted fine- to medium-grained sands are found in quantity is considered to prove that this feature develops by eolian transportation, as it is inconceivable that any form of selective transportation could have carried the frosted grains from elsewhere and left behind the unfrosted grains at places where frosted grains of small dimension do not seem to develop. It is concluded that sands of dimensions less than 1 mm. in diameter do not become frosted on beaches, but acquire this feature in eolian transportation. That does not imply that a deposit of fine-grained sandstone containing many rounded particles with frosted surfaces was produced by eolian deposition. The agent of deposition may have been water. Depositional structures may be relied on to indicate the agent of deposition.

EXAMINATION OF SANDS FROM SEVERAL ENVIRONMENTS

River sands from many parts of the United States and some parts of Canada have been examined and unless sources of rounded grains of small dimension were available all showed rather high degrees of angularity on all quartz particles less than ½ mm. in diameter and few particles of sand dimension showed much rounding. The fine-grained sands brought to the sea by the Columbia River have already been mentioned. River sands on the south half of the coast of Oregon have been studied in detail. These sands were collected from the seashore to around 30 miles up stream

and all may be described as very angular.

Beach sands from many parts of the world have been examined. Calcite sands from Hawaii and from some islands of the South Pacific have a rather high degree of rounding with many grains extremely highly polished. Quartz sands from the Oregon coast for about 20 miles south of the Columbia River and on the coast of Washington for an unknown distance north are very angular. On the coast of Oregon from Tillamook Head to the mouth of the Pistol River, a distance of about 250 miles, the beach sands range from very angular to well rounded. Sands in old placer mines on elevated terraces are generally rather well rounded. Some of the concentration of well-rounded grains is due to selective transportation, but most of the sands of these beaches are very old and have been battered around on the beaches for millions of years. Beach sands from Golden Gate Park in San Francisco, Carmel and Pebble beaches south of San Francisco, shores of Monterey Bay, hundreds of places on the beaches of the Island of Anticosti, many places on the coast of Labrador from the Bay of Seven Islands on the west to Pillage Bay on the east, Virginia Beach on the coast of Virginia south of the entrance to Chesapeake Bay. Squirrel Harbor on Hudson Bay, and places on the beaches of Hawaii are, in general, poorly rounded. Some well rounded grains are commonly present in every sample and some samples contain many well rounded grains. On the other hand, sands of dimension greater than 1 mm. in diameter are rarely highly angular and most are well rounded. The generally universal occurrence of angularity in the grains of small dimension is either due to selective sorting, or that little rounding of small grains is done on beaches. If due to selective transportation, where have the well-rounded grains gone? Some may be in patches on the beaches and some may have been moved out to sea. It was thought that perhaps the rounded grains might have been carried into the shore dunes. Examination of the sands of the shore dunes of the Oregon coast and Virginia Beach showed that these sands have about the same degree of angularity and rounding as the sands of the adjacent beaches. The examination suggests that rounded grains of quartz of small dimensions are not developed on beaches.

Dune sands from many localities have been examined. Dune sands on the Oregon and Washington coasts about the mouth of the Columbia River show no rounding whatsoever. These sands were derived from the adjacent beaches and have been transported by the winds for only short distances. Other dunes on the Oregon coast to as far south as the mouth of Pistol River contain fine-grained quartz sands which differ little in degree of roundness from similar sands on the adjacent beaches and there are generally few rounded very small grains in either the assemblages on the beaches or in the dunes. Transportation of the sands of the beaches by the waves has been long, that by the winds to place the sands in the dunes has been short. Most grains in the dunes have shiny surface but there are occasional grains which have frosted surfaces. Sands from a dune near Golden Gate Park, San Francisco, is largely composed of angular grains, but some are rounded. A sand from the Indiana dunes on the east shore of Lake Michigan is composed of about half of angular grains showing little to no rounding and the other half is of fairly well rounded grains with frosted surfaces. Sand collected from a dune near Manistique, Michigan, one mile inland from Lake Michigan contains many well rounded grains with frosted surfaces, but there are also some angular grains. Sand from a dune on the Atlantic Coast in Virginia on Cape Henry is fine-grained and is mostly composed of angular grains.

Sand from a dune in the valley of the Wisconsin River about 3 miles west of Mazomanie, Wisconsin, is largely composed of rounded to well-rounded grains

of which most have frosted surfaces. This sand was derived from the Wisconsin River and is probably largely of outwash origin with derivation from the Cambrian sandstones. As many of the sandstones are composed of well-rounded grains, there is no assurance that the rounding present in the dune sands was done by the winds, but as few of the grains in the Cambrian sandstones are frosted, it may be assumed that the wind is responsible for this feature. Well rounded sands with frosted surfaces were collected from dunes on the Camp McCoy Military Reservation near Sparta, Wisconsin. These sands were derived from the valley of the LaCrosse River to the west and may well have been rounded before they were transported by the wind. Some of these sands were derived from the Cambrian sandstones and were already well rounded at the time of release from these sandstones. Hence, these dune sands have little significance with respect to the extent of rounding which may be referred to the wind. Dune sand collected on U. S. Highway 13 south of Wisconsin Rapids. Wisconsin, has a high degree of rounding, high sphericity, and well frosted surfaces. These were originally outwash sands and have been moved around in this region by wind since the departure of the Wisconsin glacier. Sands similar as to origin and extent of transportation were collected on Highway 80 about 2 miles south of Necedah, Wisconsin. These sands are well rounded and have frosted surfaces. In both of these cases the original sedimentary terranes of derivation were the Cambrian sandstones and it is probable that the sand grains were round before entrance into the outwash. As the sands in the Cambrian sandstones are not frosted, it may be concluded that this characteristic was acquired during the wind transportation.

A dune sand from about 45 miles east of Roswell, New Mexico, is composed of poorly sorted rounded grains with frosted surfaces. The sands were acquired by the wind from sands transported by streams. A sand collected on the lee side of a dune about 25 miles north of Socorro, New Mexico, is composed of poorly sorted angular grains of which many have frosted surfaces. Sands collected from a small dune about half way between Holbrook and Winslow, Arizona, consists mostly of angular grains among which are a few rounded grains with frosted surfaces. A sand from a depression in a lava flow near Amboy Crater, Mohave Desert, California, which was placed where found by wind, contains a few frosted rounded grains, but most grains are angular and shiny. All of the sands described in this paragraph seem to have experienced short wind transportation and to have been derived from stream deposits in the immediate vicinity.

Desert sands which are believed to be of long travel were collected in New Mexico and the Desert of Gobi. The one from New Mexico was collected near Tuba City. These sands are reddish due to staining by iron oxide, and some, perhaps all, originated from Triassic and Jurassic sandstones of the region and hence have a long transportation history back of them of which a part was done by wind. The sands are very fine-grained, highly rounded and many have frosted surfaces. Sands from the Desert of Gobi were collected by Doctor C. P. Berkey from live dunes. The sands are composed of a considerable variety of minerals, are very fine grained, are extremely well rounded even to the smallest grains, and all grains have frosted surfaces.

GENERAL CONCLUSIONS

As a consequence of examination of sands from many localities of the three environmental conditions of streams, beaches, and dunes, the writer is of the opinion that the rounding of grains of sands is largely if not entirely done in traction transportation, that grains of quartz of sand dimension are very little if at all rounded in streams, and that grains of quartz of $\frac{1}{4}$ mm. or less diameter

are very little if at all rounded in aqueous transportation on sea or lake shores. It is thought that rounding of grains of ¼ to ½ mm. in diameter may be done on beaches in connection with traction transportation, but that an extremely long time would be required. Rounding of grains larger than ½ mm. in diameter seems to be easily done in traction transportation on beaches if one may judge from the commonness of rounded grains of this dimension in beach deposits. For the same distance traveled it seems certain that rounding of sand grains of the specific gravity and hardness of quartz and ½ or less mm. in diameter is far more rapidly done in traction transportation by wind than traction transportation by water, but in traction transportation many thousands of miles of travel can be considered to be required to produce well rounded grains of quartz in the ¼ to ½ mm. grade and generally more than one cycle of erosion, transportation and deposition would be necessary. Much shorter time is required round particles of calcite and many sands on the beaches of Bermuda, Hawaii and other places are composed of well rounded shell particles which seem to have been produced in a very short time.

Any assemblage of sands from any beach may be compared to the passengers on a large transoceanic passenger steamship. There are passengers of varied ancestry and many sizes and colors. They hail from many lands and many languages are spoken. Most sand assemblages on most beaches have the same heterogeneous origins. Most sands on most beaches and in most dunes have been successively transported by wind and water. This is illustrated by sands collected in dunes on Camp McCoy in western Wisconsin. The sands for these dunes were brought to them from the flood plain of the La Crosse River to the west. The river obtained the sands from Cambrian sandstones across whose outcrops the river flows, from the St. Peter sandstones which once overlay the region, and from outwash sands of the Wisconsin glacier. Grains in both the Cambrian and St. Peter sandstones are well rounded in many beds. The St. Peter sands seem best interpreted as water deposited after reworking sands of dunes, the dunes having been formed in early Ordovician time following emergence of the Prairie du Chien limestones. The dunes probably obtained the sands from Cambrian sandstones. The outwash sands were derived from all formations over which the Wisconsin glacier passed and thus may have come from any formation from the oldest system of rocks to the Pleistocene. Ultimately many of the sands were derived from Pre-Cambrian formations. With this complexity of history, of what value is any expression of rounding accomplished during the last transportation? This complexity of origin must be considered in the examination of any sand collected from any environment. Work like that of Theil shows the slowness of rounding of quartz grains in aqueous traction transportation after many miles of travel and the work of Knight shows how quickly this may be done in eolian transportation.

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ANNOUNCEMENTS

THE MIGRATION AND ACCUMULATION OF PETROLEUM AND NATURAL GAS

Publication of volume 40, number 1 of the *Quarterly* of the Colorado School of Mines has been announced by the Department of Publications. This, the January 1945 issue of the *Quarterly*, contains "The Migration and Accumulation of Petroleum and Natural Gas" by F. M. Van Tuyl and Ben H. Parker of the Department of Geology of the School of Mines and W. W. Skeeters of the Mountain Fuel Supply Company.

The publication comprises 112 pages and includes four illustrations and a bibliography of more than 100 references. Following a discussion of the extent, character, and time of migration, the factors bearing on the problem are analyzed, and the prevailing theories on migration and accumulation are then reviewed and weighed in the light of evidence gleaned from the literature and the opinions of leading petroleum geologists.

The research resulting in the publication was done under the sponsorship of the Research Committee of the American Association of Petroleum Geologists.

Copies of this number of the *Quarterly* may be obtained from the Department of Publications, Colorado School of Mines, Golden, Colorado, at $1.50 postpaid.

THIRD ANNUAL REVIEW OF PETROLEUM GEOLOGY

Publication of volume 40, number 2, of the *Quarterly* of the Colorado School of Mines has been announced by the Department of Publications. This, the April 1945 issue of the *Quarterly* contains the third annual "Review of Petroleum Geology in 1944" by F. M. Van Tuyl and W. S. Levings of the department of geology at the School of Mines, assisted by other members of the departments of geology, geophysics, and petroleum engineering.

This publication comprises 136 pages, the last 35 being devoted to a comprehensive bibliography. The subject matter includes important news items and constructive developments in basic geology as well as in petroleum geology and borderline fields, as revealed by a search of the literature and the canvas of several leading workers in the petroleum industry. The most important contributions to the literature of more than general interest are digested. Other publications of more local interest are listed in the bibliography. The Review was compiled under the sponsorship of the American Association of Petroleum Geologists.

Copies of this number of the *Quarterly* may be obtained from the Department of Publications, Colorado School of Mines, Golden, Colorado at $1.00 postpaid.

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